NEW PHYSICS AT LOW ENERGIES AND DARK MATTER-DARK ENERGY TRANSMUTATION

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A field theory is proposed where the regular fermionic matter and the dark fermionic matter can be different states of the same "primordial" fermion fields. In regime of the fermion densities typical for normal particle physics, the primordial fermions split into three families identified with regular fermions. When fermion energy density becomes comparable with dark energy density, the theory allows transition to new type of states. The possibility of such Cosmo-Low Energy Physics (CLEP) states is demonstrated by means of solutions of the field theory equations describing FRW universe filled with homogeneous scalar field and uniformly distributed nonrelativistic neutrinos. Neutrinos in CLEP state are drawn into cosmological expansion by means of dynamically changing their own parameters. One of the features of the fermions in CLEP state is that in the late time universe their masses increase as $a^{3/2}$ ($a = a(t)$ is the scale factor). The energy density of the cold dark matter consisting of neutrinos in CLEP state scales as a sort of dark energy; this cold dark matter possesses negative pressure and for the late time universe its equation of state approaches that of the cosmological constant. The total energy density of such universe is less than it would be in the universe free of fermionic matter at all.

1. Main ideas of the Two Measures Theory and the scale invariant model

The Two Measures Theory (TMT) is a generally coordinate invariant theory where the action has the form

$$S = \int L_1 \Phi d^4x + \int L_2 \sqrt{-g} d^4x \tag{1}$$

including two Lagrangians L_1 and L_2 and two measures of the volume elements (Φd^4x and $\sqrt{-g}d^4x$ respectively). One is the usual measure of integration $\sqrt{-g}$ in the 4-dimensional space-time manifold equipped by the metric $g_{\mu\nu}$. Another is also a scalar density built of four scalar fields φ_a ($a = 1,2,3,4$), $\Phi = \varepsilon^{\mu\nu\alpha\beta}\varepsilon_{abcd}\partial_\mu\varphi_a\partial_\nu\varphi_b\partial_\alpha\varphi_c\partial_\beta\varphi_d$. It is assumed

that the Lagrangians L_1 and L_2 are functions of the matter fields, the dilaton field, the metric, the connection (or spin-connection) but not of the "measure fields" φ_a. Varying φ_a, we get $B^{\mu}_{a}\partial_{\mu}L_1 = 0$ where $B^{\mu}_{a} = \varepsilon^{\mu\nu\alpha\beta}\varepsilon_{abcd}\partial_{\nu}\varphi_b\partial_{\alpha}\varphi_c\partial_{\beta}\varphi_d$. Since $Det(B^{\mu}_{a}) = \frac{4^{-4}}{4!}\Phi^3$ it follows that if $\Phi \neq 0$, $L_1 = sM^4 = const$ where $s = \pm 1$ and M is a constant of integration with the dimension of mass. Important feature of TMT that is responsible for many interesting and desirable results of the field theory models studied so far[1]-[10] (see also [5]) consists of the assumption that all fields, including also metric, connection (or vierbein and spin-connection) and the measure fields φ_a are independent dynamical variables.

As it has been shown earlier, in TMT there is no a need to postulate the existence of three species for each type of fermions (like three neutrinos, three charged leptons, etc.) but rather this is achived as a dynamical effect of TMT in normal particle physics conditions. The matter content of our model includes the dilaton scalar field ϕ, two so-called primordial fermion fields (the neutrino primordial field ν and the electron primordial field E) and electromagnetic field A_μ. Generalization to the non-Abelian gauge models including Higgs fields and quarks is straightforward[7]. To simplify the presentation of the ideas we ignore also the chiral properties of neutrino; this can be done straightforward and does not affect the main results.

Keeping the general structure (1), it is convenient to represent the action in the following form:

$$
\begin{aligned}
S = &\int d^4x e^{\alpha\phi/M_p}(\Phi + b\sqrt{-g})\left[-\frac{1}{\kappa}R(\omega, e) + \frac{1}{2}g^{\mu\nu}\phi_{,\mu}\phi_{,\nu}\right] \\
&- \int d^4x e^{2\alpha\phi/M_p}[\Phi V_1 + \sqrt{-g}V_2] - \int d^4x\sqrt{-g}\frac{1}{4}g^{\alpha\beta}g^{\mu\nu}F_{\alpha\mu}F_{\beta\nu} \\
&+ \int d^4x e^{\alpha\phi/M_p}(\Phi + k\sqrt{-g})\frac{i}{2}\sum_i \overline{\Psi}_i\left(\gamma^a e^{\mu}_{a}\overrightarrow{\nabla}^{(i)}_{\mu} - \overleftarrow{\nabla}^{(i)}_{\mu}\gamma^a e^{\mu}_{a}\right)\Psi_i \\
&- \int d^4x e^{\frac{3}{2}\alpha\phi/M_p}\left[(\Phi + h_\nu\sqrt{-g})\mu_\nu\overline{\nu}\nu + (\Phi + h_E\sqrt{-g})\mu_E\overline{E}E\right] \qquad (2)
\end{aligned}
$$

where where Ψ_i ($i = \nu, E$) is the general notation for the primordial fermion fields ν and E, V_1 and V_2 are constants, $F_{\alpha\beta} = \partial_\alpha A_\beta - \partial_\beta A_\alpha$, μ_ν and μ_E are the mass parameters, $\overrightarrow{\nabla}^{(\nu)}_{\mu} = \overrightarrow{\partial}_{\mu} + \frac{1}{2}\omega^{cd}_{\mu}\sigma_{cd}$, $\overrightarrow{\nabla}^{(E)}_{\mu} = \overrightarrow{\partial}_{\mu} + \frac{1}{2}\omega^{cd}_{\mu}\sigma_{cd} + ieA_\mu$; $R(\omega, e) = e^{a\mu}e^{b\nu}R_{\mu\nu ab}(\omega)$ is the scalar curvature, e^{μ}_{a} and ω^{ab}_{μ} are the vierbein and spin-connection; $g^{\mu\nu} = e^{\mu}_{a}e^{\nu}_{b}\eta^{ab}$ and $R_{\mu\nu ab}(\omega) = \partial_\mu\omega_{\nu ab} + \omega^{c}_{\mu a}\omega_{\nu cb} - (\mu \leftrightarrow \nu)$; constants b, k, h_i are dimensionless parameters.

The action (2) is invariant under the global scale transformations

$$e^a_\mu \to e^{\theta/2} e^a_\mu, \quad \omega^\mu_{ab} \to \omega^\mu_{ab}, \quad \varphi_a \to \lambda_a \varphi_a \quad where \quad \Pi\lambda_a = e^{2\theta}$$
$$A_\alpha \to A_\alpha, \quad \phi \to \phi - \frac{M_p}{\alpha}\theta, \quad \Psi_i \to e^{-\theta/4}\Psi_i, \quad \overline{\Psi}_i \to e^{-\theta/4}\overline{\Psi}_i. \qquad (3)$$

One can show that except for a few special choices providing positivity of the energy and the right chiral structure in the Einstein frame, Eq.(2) describes *the most general TMT action satisfying the formulated above symmetries.*

2. Constraint and equations of motion in the Einstein frame

Variation of the measure fields φ_a with the condition $\Phi \neq 0$ leads, as we have already seen in Sec.2, to the equation $L_1 = sM^4$ where L_1 is now defined, according to Eq. (1), as the part of the integrand of the action (2) coupled to the measure Φ. The appearance of a nonzero integration constant sM^4 spontaneously breaks the scale invariance (3). One can see that the measure Φ degrees of freedom appear in all the equations of motion only through dependence on the scalar field $\zeta \equiv \Phi/\sqrt{-g}$. In particular, the gravitational and all matter fields equations of motion include noncanonical terms proportional to $\partial_\mu\zeta$. It turns out that with the set of the new variables (ϕ and A_μ remain the same)

$$\tilde{e}_{a\mu} = e^{\frac{1}{2}\alpha\phi/M_p}(\zeta+b)^{1/2} e_{a\mu}, \quad \Psi'_i = e^{-\frac{1}{4}\alpha\phi/M_p}\frac{(\zeta+k)^{1/2}}{(\zeta+b)^{3/4}}\Psi_i \qquad (4)$$

which we call the Einstein frame, the spin-connections become those of the Einstein-Cartan space-time and the noncanonical terms proportional to $\partial_\mu\zeta$ disappear from all equations of motion. Since $\tilde{e}_{a\mu}$, ν' and E' are invariant under the scale transformations (3), spontaneous breaking of the scale symmetry (3) (by means of equation $L_1 = sM^4$) is reduced in the new variables to the *spontaneous breaking of the shift symmetry* $\phi \to \phi + const$.

The gravitational equations in the Einstein frame take the standard GR form $G_{\mu\nu}(\tilde{g}_{\alpha\beta}) = \frac{\kappa}{2}T^{eff}_{\mu\nu}$ where

$$T^{eff}_{\mu\nu} = K_{\mu\nu} + \tilde{g}_{\mu\nu}V_{eff}(\phi;\zeta) + T^{(em)}_{\mu\nu} + T^{(f,can)}_{\mu\nu} + T^{(f,noncan)}_{\mu\nu} \qquad (5)$$

Here $K_{\mu\nu} = \phi_{,\mu}\phi_{,\nu} - \frac{1}{2}\tilde{g}_{\mu\nu}\tilde{g}^{\alpha\beta}\phi_{,\alpha}\phi_{,\beta}$, $G_{\mu\nu}(\tilde{g}_{\alpha\beta})$ is the Einstein tensor in the Riemannian space-time with the metric $\tilde{g}_{\mu\nu}$; the function $V_{eff}(\phi;\zeta)$ has the form

$$V_{eff}(\phi;\zeta) = \frac{b\left(sM^4 e^{-2\alpha\phi/M_p} + V_1\right) - V_2}{(\zeta+b)^2}; \qquad (6)$$

$T^{(em)}_{\mu\nu}$ is the canonical energy momentum tensor for the electromagnetic field; $T^{(f,can)}_{\mu\nu}$ is the canonical energy momentum tensor for (primordial) fermions ν' and E' in curved space-time including also standard electromagnetic interaction of E'. $T^{(f,noncan)}_{\mu\nu}$ is the *noncanonical* contribution of the fermions into the energy momentum tensor

$$T^{(f,noncan)}_{\mu\nu} = -\tilde{g}_{\mu\nu}\sum_i F_i(\zeta)\overline{\Psi'}_i\Psi'_i \equiv \tilde{g}_{\mu\nu}\Lambda^{(ferm)}_{dyn} \tag{7}$$

where $i=\nu', E'$ and

$$F_i(\zeta) \equiv \frac{\mu_i}{2(\zeta+k)^2(\zeta+b)^{1/2}}[\zeta^2+(3h_i-k)\zeta+2b(h_i-k)+kh_i]. \tag{8}$$

The structure of $T^{(f,noncan)}_{\mu\nu}$ shows that it is originated by fermions but behaves as a sort of variable cosmological constant. This is why we will refer to it as *dynamical fermionic* Λ *term* $\Lambda^{(ferm)}_{dyn}$. One has to emphasize the substantial difference of the way $\Lambda^{(ferm)}_{dyn}$ emerges here as compared to the models of the condensate cosmology (see for example Ref.[12]). As we will see in the next sections, Λ^{ferm}_{dyn} becomes negligible in gravitational experiments with observable matter. However it may be very important for some astrophysics and cosmology problems.

The dilaton ϕ field equation in the new variables reads

$$\Box\phi - \frac{\alpha}{M_p(\zeta+b)}\left[sM^4e^{-2\alpha\phi/M_p} - \frac{(\zeta-b)V_1+2V_2}{\zeta+b}\right] = -\frac{\alpha}{M_p}\sum_i F_i\overline{\Psi'_i}\Psi'_i \tag{9}$$

where $\Box\phi = (-\tilde{g})^{-1/2}\partial_\mu(\sqrt{-\tilde{g}}\tilde{g}^{\mu\nu}\partial_\nu\phi)$.

Equations for the primordial leptons in terms of the variables (4) take the standard form of fermionic equations in the Einstein-Cartan space-time where the standard electromagnetic interaction presents also. All the novelty consists of the form of the ζ depending "masses" $m_i(\zeta)$ of the primordial fermions ν', E':

$$m_i(\zeta) = \frac{\mu_i(\zeta+h_i)}{(\zeta+k)(\zeta+b)^{1/2}} \qquad i=\nu', E'. \tag{10}$$

It should be noticed that change of variables we have performed by means of Eq.(4) provide also a conventional form of the covariant conservation law of fermionic current $j^\mu = \overline{\Psi}'\gamma^a\tilde{e}^\mu_a\Psi'$.

The scalar field ζ in the above equations is defined by the constraint which is the consistency condition of equations of motion, see for example[5].

In the Einstein frame (4) the constraint takes the form

$$-\frac{1}{(\zeta+b)^2}\left\{(\zeta-b)\left[sM^4e^{-2\alpha\phi/M_p}+V_1\right]+2V_2\right\}=\sum_i F_i\overline{\Psi'_i}\Psi'_i. \qquad (11)$$

Generically the constraint (11) determines ζ as a very complicated function of ϕ, $\overline{\nu'}\nu'$ and $\overline{E'}E'$. However, there are a few very important particular situations where the theory allows exact solutions of great interest[6],[7].

3. Some limiting cases of physical interest

In a typical particle physics situation, say detection of a single fermion, the measurement implies a localization of the fermion which is expressed in developing a very large value of $|\overline{\Psi'}\Psi'|$. According to the constraint (11) this is possible if $F_i(\zeta)\approx 0$, $i=\nu', E'$ (which gives two constant solutions for ζ) or $\zeta\approx -b$. These solutions allow to describe the effect of splitting of the primordial fermions into three generations of the regular fermions (for details see [6],[7],citeproceed-2001). It is interesting also that for the first two generations (which we associate with the solutions where $F_i(\zeta)\approx 0$) their coupling to the dilaton ϕ is automatically strongly suppressed, as it follows from Eq.(9), which provides a solution of the fifth force problem (about the role of the symmetry $\phi\rightarrow\phi+const$ see Ref.[11])

In the case of the complete absence of massive fermions the constraint determines ζ as the function of ϕ: $\zeta=b-2V_2/(V_1+sM^4e^{-2\alpha\phi/M_p})$. The effective potential of the scalar field ϕ results then from Eq.(6)

$$V^{(0)}_{eff}(\phi)\equiv V_{eff}(\phi;\zeta)|_{\overline{\psi'}\psi'=0}=\frac{(V_1+sM^4e^{-2\alpha\phi/M_p})^2}{4[b(V_1+sM^4e^{-2\alpha\phi/M_p})-V_2]}. \qquad (12)$$

Assuming $bV_1>V_2$ and $s=+1$ we see that the asymptotic (as $\phi\rightarrow\infty$) value of $V^{(0)}_{eff}$ is the positive cosmological constant $\Lambda^{(0)}=\frac{V_1^2}{4(bV_1-V_2)}$. If $2V_2>bV_1>V_2$ then $V^{(0)}_{eff}$ has the absolute minimum $V^{(0)}_{eff,min}=V_2/b^2$ at $\phi=\phi_{min}=(M_p/2\alpha)\ln[bM^4/(2V_2-bV_1)]$.

4. Cosmo-Low Energy Physics states

It turns out that besides the normal fermion vacuum where the fermion contribution to the constraint is totally negligible, TMT predicts possibility of so far unknown states which can be realized, for example, in astrophysics and cosmology. Let us study a toy model[10] where in addition to the homogeneous scalar field ϕ, the spatially flat universe is filled also with uniformly distributed nonrelativistic neutrinos as a model of dark matter. Spreading

of the neutrino wave packets during their free motion lasting a long time yields extremely small values of $\overline{\Psi}'\Psi' = u^\dagger u$ (u is the large component of the Dirac spinor Ψ'). There is a solution where the decaying fermion contribution $u^\dagger u \sim \frac{const}{a^3}$ to the constraint is compensated by approaching $\zeta \to -k$. Then solving (11) for ζ we have to take into account both sides of the constraint. After averaging over typical cosmological scales (resulting in the Hubble low), the constraint (11) reads

$$-(k+b)\left(sM^4 e^{-2\alpha\phi/M_p} + V_1\right) + 2V_2 + (b-k)^2 \frac{n_0^{(\nu)}}{a^3} F_\nu(\zeta)|_{\zeta\approx -k} = 0 \quad (13)$$

where $F_\nu(\zeta)|_{\zeta\approx -k} = \mu_\nu(h_\nu - k)(b-k)^{1/2}(\zeta+k)^{-2} + O((\zeta+k)^{-1})$ and $n_0^{(\nu)}$ is a constant determined by the total number of the cold neutrinos.

Cosmological equations are then as following

$$\left(\frac{\dot a}{a}\right)^2 = \frac{1}{3M_p^2}\left[\rho_\phi + \rho_{clep}\right] \quad (14)$$

$$\ddot\phi + 3\frac{\dot a}{a}\dot\phi + \frac{2\alpha k}{(b-k)^2 M_p} M^4 e^{-2\alpha\phi/M_p} + O\left((\zeta+k)e^{-2\alpha\phi/M_p}\right) = 0 \quad (15)$$

where

$$\rho_\phi = \frac{1}{2}\dot\phi^2 + \frac{bV_1 - V_2}{(b-k)^2} + \frac{b}{(b-k)^2} sM^4 e^{-2\alpha\phi/M_p} + O(\zeta+k), \quad (16)$$

$$\rho_{clep} = \left[\frac{\mu_\nu(h_\nu - k)}{(\zeta+k)(b-k)^{1/2}} - F_\nu(\zeta)|_{\zeta\approx -k}\right]\frac{n_0^{(\nu)}}{a^3} \quad (17)$$

The corrections $O(\zeta+k)$ behave as $O(\zeta+k) \propto a^{-3/2}$ and it turns out that they are negligible if no fine tuning of the parameters of the theory will be done. We choose $s = +1$ and assume here that $V_1 > 0,\ V_2 > 0 \quad and \quad b > 0,\ k < 0,\ h_\nu < 0,\ h_\nu - k < 0,\ b + k < 0$. In the case we work with a positive fermion energy solution, in order to provide positivity of the effective neutrino mass (see Eq.(10)) in the CLEP state, we should consider the regime where $\zeta = -k - \varepsilon$, $\varepsilon > 0$. Then $F_\nu(\zeta)|_{\zeta\approx -k} < 0$ and both of the terms in Eq.(17) are positive. The first term in Eq.(17) results from the canonical part $T_{00}^{(\nu,can)}$ of the neutrino energy-momentum tensor after making use of the equations for neutrino field, neglecting the terms proportional to 3-momenta of the neutrinos and averaging. The second term in Eq.(17) comes from the dynamical fermionic $\Lambda_{dyn}^{(ferm)}$ term.

Neglecting in (17) terms of the order of $(\zeta+k)^{-1}$ as compared to the terms of the order of $(\zeta+k)^{-2}$ and using again the constraint (13) we obtain

for the pressure and density of the uniformly distributed neutrino in the CLEP state

$$P_{clep} = -\rho_{clep} = \frac{2V_2 + |b+k|V_1}{(b-k)^2} + \frac{|b+k|}{(b-k)^2} M^4 e^{-2\alpha\phi/M_p} \tag{18}$$

which is typical for the dark energy sector including both a cosmological constant and an exponential ϕ-potential (compare (18) with (16)). The accuracy of this approximation grows as $a(t) \to \infty$.

The total energy density and the total pressure (including both the scalar field ϕ and neutrinos in CLEP state) in the framework of the explained above approximations can be represented in the form

$$\rho_{dark}^{(total)} \equiv \rho_\phi + \rho_{clep} = \frac{1}{2}\dot{\phi}^2 + U_{dark}^{(total)}(\phi) \tag{19}$$

$$P_{dark}^{(total)} \equiv P_\phi + P_{clep} = \frac{1}{2}\dot{\phi}^2 - U_{dark}^{(total)}(\phi), \tag{20}$$

where the effective potential $U_{dark}^{(total)}(\phi) = \Lambda + V_{quint}(\phi)$, where

$$\Lambda = \frac{V_2 + |k|V_1}{(b-k)^2}, \qquad V_{quint}(\phi) = \frac{|k|}{(b-k)^2} M^4 e^{-2\alpha\phi/M_p}. \tag{21}$$

This means that the evolution of the late time universe in the state with $\zeta \approx -k$ proceeds as it would be in the standard field theory model (non-TMT) including *both the cosmological constant and the quintessence-like field ϕ with the exponential potential*. Note that to provide the observable energy densities (for example, $\Lambda \sim \rho_{crit}$, where ρ_{crit} is the present day critical energy density) there is no need of fine tuning of the dimensionfull parameters V_1 and V_2 but instead one can assume that the dimensionless parameters b, k are very large.

It is very interesting to compare the effective potential $V_{eff}^{(0)}(\phi)$, Eq.(12), predicted for the universe filled only with the homogeneous scalar field (for short, a state "absent of fermions"), on the one hand, with the effective dark sector potential $U_{dark}^{(total)}(\phi)$ for the universe filled both with the homogeneous scalar field and with the uniformly distributed nonrelativistic neutrinos (for short, "CLEP state"), on the other hand. The *remarkable result* consists in the fact that if $bV_1 > V_2$, which is needed for positivity of $\Lambda^{(0)}$, then

$$V_{eff}^{(0)}(\phi) - U_{dark}^{(total)}(\phi) \equiv \frac{\left[\frac{b+k}{2}\left(V_1 + M^4 e^{-2\alpha\phi/M_p}\right) - V_2\right]^2}{4(b-k)^2\left[b\left(V_1 + M^4 e^{-2\alpha\phi/M_p}\right) - V_2\right]} > 0. \tag{22}$$

This means that (for the same value of $\dot{\phi}^2$) *the universe in "the CLEP state" has a lower energy density than the one in the "absent of fermions" state*. One should emphasize that this result does not imply at all that ρ_{clep} is negative.

For illustration of what kind of solutions one can expect, let us take the *particular value* for the parameter α, namely $\alpha = \sqrt{3/8}$. Then in the framework of the explained above approximations, the cosmological equations allow the following analytic solution:

$$\phi(t) = \frac{M_p}{2\alpha}\varphi_0 + \frac{M_p}{2\alpha}\ln(M_p t), \qquad a(t) \propto t^{1/3}e^{\lambda t}, \tag{23}$$

where

$$\lambda = \frac{1}{M_p}\sqrt{\frac{\Lambda}{3}}, \qquad e^{-\varphi_0} = \frac{2(b-k)^2 M_p^2}{\sqrt{3}|k|M^4}\sqrt{\Lambda}. \tag{24}$$

The mass of the neutrino in such CLEP state increases exponentially in time and its ϕ dependence is double-exponential:

$$m_\nu|_{CLEP} \sim a^{3/2}(t) \sim t^{1/2}e^{\frac{3}{2}\lambda t} \sim \exp\left[\frac{3\lambda e^{-\varphi_0}}{2M_p}\exp\left(\frac{2\alpha}{M_p}\phi\right)\right]. \tag{25}$$

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